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Multi-Component Dark Matter

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We explore multi-component dark matter models where the dark sector consists of multiple stable states with different mass scales, and dark forces coupling these states further enrich the dynamics. The multi-component nature of the dark matter naturally arises in supersymmetric models, where both R parity and an additional symmetry, such as a Z_2, is preserved. We focus on a particular model where the heavier component of dark matter carries lepton number and annihilates mostly to leptons. The heavier component naturally explains the PAMELA, ATIC and synchrotron signals, without an excess in antiprotons which typically mars other models of weak scale dark matter. The lighter component, which may have a mass from a few GeV to a TeV, may explain the DAMA signal, and may be visible in low threshold runs of CDMS and XENON, which search for light dark matter.

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INTRODUCTION

There have been many tantalizing signals which may be evidence for particle dark matter. Most recently, the PAMELA experiment has reported an cosmic ray positron excess of positrons with energy in the 10-100 GeV range [1], which is consistent with annihilating dark matter [2], confirming the excess observed by the HEAT [3] and AMS [4] experiments. The ATIC and PPB-BETS balloon experiments have likewise observed an excess, consistent with the PAMELA, HEAT and AMS results. ATIC and PPB-BETS suggest a dark matter particle annihilating to leptons with mass in the 500-800 GeV range [5]; the other observations are consistent with mass in this range. In addition, there is the observation of the synchrotron radiation toward the galactic center, the so-called "WMAP haze," which is indicative of dark matter annihilating to electrons which emit photons in the galactic magnetic field [6]. Indeed, an annihilation cross-section to e^+e^- which produces the WMAP haze is roughly the right size (up to a boost factor) to produce the AMS, HEAT, ATIC, PPB-BETS and PAMELA excesses. The size of these signals is also roughly consistent with the freeze-out annihilation cross-section predicted for a thermal relic WIMP. In direct detection, the DAMA experiment has reported an 8.2σ significance modulation in the rate of recoils in their experiment [7]. The phase and amplitude of their signal is consistent with a light elastically scattering WIMP with mass in the $\sim 3-10$ GeV range [8].

While these signals are intriguing, detailed explanations of these signals in terms of standard models of WIMP dark matter, such as supersymmetry, may be challenging. One difficulty in explaining the AMS, HEAT, PAMELA, ATIC, PPB-BETS and haze excesses is that the dark matter must have a large annihilation cross-section to leptons and a small annihilation cross-section to hadrons, since the data shows a positron excess but no excess of anti-protons [1, 9, 10]. This is challenging for two reasons. First, hadrons carry an enhancement in the annihilation cross-section which goes like N_c, the number of colors; hence in many models, annihilation to colored particles is the preferred mode. Secondly, when the dark matter particle is Majorana, as in SUSY models, there is a chiral suppression which disfavors annihilation to light modes. In SUSY, annihilation to $\bar{b}b$, $\tau^+\tau^-$, and W^+W^- is preferred; it has been shown that an annihilation cross-section big enough to produce the positron excess through this mode will produce too many anti-protons through the hadronic decays of these states (see e.g. [11] for the case of W^+W^-).

In this paper we develop models which naturally overcome this challenge, where the dark matter effectively carries lepton number, and hence annihilation to leptons is the only mode allowed. We also show that within this class of models, the dark matter may in fact also quite naturally be multi-component. A heavier component explains the PAMELA, ATIC, PPB-BETS and synchrotron excesses, while the lighter component, residing in the hidden sector, typically has a much lower mass, and may explain the DAMA signal. In certain of the models we discuss here, the lighter component may have its mass set by the baryon asymmetry, rather than thermal freezeout, as discussed in [12]. In this case, these models predict the mass of the lighter component of dark matter to be in the few GeV range, as required by DAMA. These low mass states are reachable with low threshold analyses currently being planned by the CDMS and XENON experiments [13].

The addition of these low mass hidden sectors with multi-component dark matter naturally suggests rich dynamics in the hidden sector. In many cases, there are new forces, both scalar and vector, which give rise to novel phenomenology, and in many ways, the rich dynamics of these low mass hidden sector dark matter models is motivated by the Hidden Valley [14]. The components of this model, with multiple dark forces and low mass dark matter states coupled to the SM through kinetic mixing or TeV mass states, resemble features of the low mass hidden dark matter models constructed in [12, 15, 16]. Because multiple forces may reside in the hidden sector, these models may also provide a natural context for solving a second challenge for a model of DM explaining the positron excesses. That is, there must be a boost in the annihilation of the dark matter in the halo today relative to the cross-section required at thermal freeze-out, $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^3/s. For dark matter in the 500-800 GeV range, the boost factor is typically quite large, ~ 100, for direct annihilation to e^+e^- [5, 9]. The boost factor may come from a large overdensity in the dark matter locally in the galaxy, though simulations suggest that a boost factor much larger than ~ 5 is difficult to produce. A boost factor may instead imply that the size of the dark matter annihilation cross-section in the halo today is larger than the annihilation at thermal freeze-out. A possible source of the needed enhancement of the cross-section today is the so-called Sommerfeld effect [19]. This effect gives rise to an enhancement of the annihilation cross-section at low velocity v, so that the annihilation cross-section for particles locally in our halo ($v \sim 10^{-3}$) is enhanced with respect to the freeze-out cross-section ($v \sim 0.3$) (though see [20] for possible issues with the Sommerfeld solution). One of the additional dark forces may provide for such an enhancement. (See [21] for a model where late decay of a meta-stable state produces the needed boost.)

The outline of this paper is as follows. In the next section we summarize the basic structure of the class of models considered in this paper. We then proceed to build up in piecewise fashion the dynamics of this class of models. We first discuss the sector which carries lepton number and produces the positron excess; we term this sector the "X sector." We then show how, with the addition of supersymmetry and additional forces, this X sector provides the basic building blocks for a multi-component model of dark matter, with the presence of dark forces. Next we add an additional hidden dark matter (hDM) sector which provides a means for symmetry breaking of the new dark forces, and provides a candidate explanation for the DAMA signal. Finally, we conclude.

BASIC STRUCTURE OF THE MODELS

Although dark matter with multiple components could potentially be quite complicated, in this paper we propose that the dark sectors take on a simple basic structure. To the SM sector, we add an "X sector." The X sector contains generally high mass states and communicates to the SM through $\mathcal{O}(1)$ operators. To this sector, we may add a hidden dark matter (hDM) sector which provides a means for breaking the symmetry of the new dark forces and giving masses to the gauged mediators.

In the next sections, we build the multiple components of these models piece by piece, but we summarize the features of each model here. We begin with a non-supersymmetric X sector model. The model contains a 500-800 GeV scalar DM candidate which produces the observed PAMELA, ATIC and synchrotron excesses. It annihilates primarily to electron-positron pairs since it couples to the SM only through an operator which carries lepton number. It is stable by virtue of a Z_2 symmetry.

In the second model, we supersymmetrize the X sector. In addition to the Z_2 symmetry, R-parity keeps the lightest superpartner in the X sector stable. The scalar superpartner is 500-800 GeV, and produces the observed PAMELA, ATIC and synchrotron excesses. The fermionic component we now make light, in the 3-10 GeV range; it may explain the DAMA signal. X carries lepton number, and the number density of the light fermionic component is set by the baryon and lepton asymmetry, not by thermal freeze-out. The X sector may be charged under a new gauge group, for example a dark photon, as was recently discussed in [23].

In the third model we extend the X sector to a more complex hidden DM sector, which may contain multiple low mass fields. The hidden DM (hDM) may communicate to the standard model either through the X sector, or through mixing of a $U(1)_D$ force ("the dark force") with SM hypercharge, as was constructed in [15, 16]. The hDM sector provides for breaking of the dark force(s). Provided that the mixing between $U(1)_D$ and $U(1)_Y$ is small enough, the hidden sector is shielded from MSSM SUSY breaking by the factor $m_D \sim \theta m_{SUSY}$, where θ is the mixing, $m_{SUSY} \sim 1$ TeV are the MSSM SUSY breaking masses and m_D is the typical scale for the DM in the hidden sector. The mixing between the two sectors is typically a loop factor $\theta \sim 10^{-2} - 10^{-3}$ further motivating the low mass 1 GeV scale relevant for DAMA as an important scale in hidden dark matter sectors. This mechanism for creating hidden sectors with naturally light scalars and light gauge bosons was introduced in the context of supersymmetric MeV dark matter [16], and was shown to be quite general for higher mass hidden sectors in the 0.1-100 GeV range [17, 18].

A MODEL FOR THE X SECTOR: LEPTONIC DARK MATTER

We begin with a simple one-component dark matter model which will explain the PAMELA, ATIC and synchrotron signals. To the standard model we add the Lagrangian

$$\Delta\mathcal{L} = y_i' L_i \tilde{H}' \tilde{X} + \lambda^2 |S|^2 |\tilde{X}|^2, \qquad (1)$$

where $\tilde{H}'$ is a fermionic electroweak doublet and $\tilde{X}$ is the scalar dark matter. There is an additional Z_2 under which both $\tilde{H}'$ and $\tilde{X}$ are odd which keeps the dark matter stable. Because the dark matter effectively carries lepton number, it annihilates predominantly to leptons (provided $y_i' > \lambda$), both in freeze-out and locally in the galaxy today. Thus the positron excess, with the absence of anti-proton excess, points to leptonically interacting dark matter, of which this Lagrangian provides a simple starting point (though see [22] for another "leptophilic" model).

We take $\tilde{X}$ to be the lighter of the Z_2 odd states, with mass in the $500 - 800$ GeV range. Thermal freeze-out occurs through t-channel exchange of $\tilde{H}'$ to SM leptons. If $m_{\tilde{H}'} \gtrsim m_{\tilde{X}}$, the annihilation cross-section is $\sigma_{\rm ann} v = y_i'^4 m_{\tilde{X}}^2/(\pi m_{\tilde{H}'}^4)$, which must be $\sigma_{\rm ann} v \simeq 3 \times 10^{-26}$cm^3/s in order to be consistent with the observed relic abundance. Thus for $m_{\tilde{X}} \approx 700$ GeV, $y_i' \lesssim 1$. With this annihilation cross-section to electron-positron pairs, the WMAP haze from DM annihilation in the galactic center is naturally produced [6]. (If X had instead been fermionic, there would be a p-wave suppressed annihilation cross-section, too small by v^2 to produce the observed positron flux today.) Such a large mass dark matter particle annihilating directly to e^+e^- requires a boost of order 100. It may happen that we are near to a large overly-dense object to produce such a boost factor. The boost may also be achieved, however, through a Sommerfeld enhancement [19] at low v in the overall annihilation rate, mediated by the singlet scalar S. This enhancement is relevant if $\lambda^2/(4\pi)m_X \gtrsim m_S$ is satisfied. This implies that S is somewhat light, in the 10 GeV range. This does not violate existing bounds, since it need only couple to the dark states. How such a light scalar can be made technically natural we discuss in the next section.

We can see that such a simple extension of the Standard Model naturally explains the PAMELA, ATIC and WMAP haze results. We turn to an extended supersymmetric model which may also accommodate DAMA.

A Supersymmetric, Multi-Component X sector Model

A supersymmetric version of the first model, Eq. (1), provides the building block for a multi-component DM model:

$$\Delta W = y_i' L_i H' \bar{X} + \lambda S \bar{X} X + \kappa S^3. \tag{2}$$

Notice that in addition to having the Z_2 symmetry of the first model (under which H' and X are odd) there is now also a conserved R-parity. In order to generate the PAMELA and ATIC signatures, one component of the leptonic X must be the dark matter particle which annihilates predominantly to electrons.

The first possibility is that the scalar $\tilde{X}$ is a weak scale candidate which gets its mass from SUSY breaking, and that this $\sim 500-800$ GeV state is the LSP. Its thermal abundance is set through t channel Higgsino exchange to e^+e^- pairs. Again, a coupling $y' \sim 1$ will give approximately the correct thermal abundance, and an annihilation cross-section sufficient to generate the PAMELA, ATIC signals, and WMAP haze.

The fermionic component of X will also be stable by the Z_2 symmetry. In the Asymmetric Dark Matter model [12], taking after the idea of [24], the mass of the dark matter particle is set by the baryon asymmetry, not by thermal freeze-out. We refer the reader to this paper for details of the mechanism, but summarize the basic scenario here. The operator Eq. (2) enforces the relation $n_X - n_{\bar{X}} \approx n_\ell - n_{\bar{\ell}} \equiv \eta_\ell$, so that the dark matter asymmetry is set by the lepton asymmetry. The lepton asymmetry in turn is related to the baryon asymmetry through the chemical equilibrium equations, so that $c\eta_b = \eta_\ell$ where c is an $\mathcal{O}(1)$ number. Thus the dark matter asymmetry is of the same size of the baryon asymmetry so that $n_X - n_{\bar{X}} \approx c(n_b - n_{\bar{b}})$. Since observationally, $5\rho_b \approx \rho_{DM}$, we have $5m_p c(n_b - n_{\bar{b}}) \approx m_X(n_X - n_{\bar{X}})$, relating the dark matter mass to the proton mass m_p. The precise calculation of [12] finds that the corresponding dark matter mass is $m_X \approx 8$ GeV, an intriguing mass window for an elastically scattering WIMP explanation of the DAMA signal [8], if the spin-independent scattering cross-section off nuclei is in the range $\sigma_{SI} \sim 10^{-41} - 10^{-39}$ cm^2, or even larger should the light dark matter state compose only a fraction of the DM, with the heavier state composing the rest.

The simplest possibility is that the dark matter couples to a new massive state, such as a Z'. The SM may carry the charges, for example, of the $U(1)_\chi$, with the dark matter X carrying the charge of a sterile neutrino for anomaly cancellation. The size of the nucleon-DM interaction cross-section is $\sigma_{SI} \simeq \frac{g^4 m_r^2}{\pi m_{Z'}^4} \sim 10^{-41}$ cm$^2 \left(\frac{2\text{ TeV}}{m_{Z'}/g}\right)^4$. Other dark forces may also mediate interaction with nuclei. For example, the singlet scalar S may mix with the Higgs through a term $\zeta S H_u H_d$ in the super-potential. The size of this scattering cross-section is

$$\begin{aligned}\sigma_{SI} &\simeq \frac{m_r^2}{\pi}\frac{\lambda^2\langle S\rangle^2\zeta^2 v_q^2}{m_{H_q}^4 m_S^4} A^2_{\bar{N}NH_q} \\ &\sim 10^{-39}\text{ cm}^2\zeta^2\left(\frac{m_{DM}}{10\text{ GeV}}\right)^2\left(\frac{100\text{ GeV}}{m_{H_q}}\right)^4\left(\frac{10\text{ GeV}}{m_S}\right)^4\end{aligned} \tag{3}$$

where v_q is the up or down-type Higgs vev, and $A_{\bar{N}NH_q} \sim f_q m_p/v_q$ is the Higgs-nucleon coupling, taken from [25] with f_q a form factor. If this singlet couples to SUSY breaking through the $\zeta S H_u H_d$ and $\lambda S\bar{X}X$ terms, tree level and one loop diagrams will generate a mass for S which is parametrically $m_S^2 \sim -(\zeta^2+\lambda^2)m_{SUSY}^2 \log\left(\frac{\Lambda}{m_{SUSY}}\right)/16\pi^2 + \zeta^2\langle H\rangle^2$, so that for ζ and λ not much smaller than 0.1, technical naturalness suggests $m_S \sim 10$ GeV, so that the scattering cross-section is in the $10^{-41}-10^{-39}$ cm^2 window for explaining the DAMA signal with light WIMPs. Alternatively, if the DAMA signal turns out not to be from DM scattering, it is easy to evade direct detection bounds by lowering the mixing ζ or correspondingly raising the mass of the mediators; these lower mass WIMPs may still be in reach of the low threshold runs of CDMS [13] and XENON.

These light scalars may mediate Sommerfeld enhancements. The enhancement for the heavy scalar X can arise naturally from single or double S scalar exchange, from the vertices $|\tilde{X}|^2|S|$ or $|\tilde{X}|^2|S|^2$. The former gives rise to an ordinary attractive Coulomb interaction. The double scalar exchange has a $1/r^3$ term in the potential, and may give rise to an enhanced attraction at small distances. For the Coulomb potential, we require $g_S^2 m_{\tilde{X}}/4\pi \gtrsim m_S$, where $g_S = \lambda\langle S\rangle/m_S$ in order to be in the Sommerfeld regime. Since the scalar mass is driven by radiative corrections, naturally we expect $m_S \sim \lambda m_{SUSY}/4\pi \sim \lambda m_{\tilde{X}}/4\pi$. Thus we see that a small hierarchy $\langle S\rangle \gg m_S$ weakens a possible tension between the presence of the Sommerfeld enhancement and technical naturalness. Other forces may also be present to mediate such a Sommerfeld enhancement. A dark force, a gauged

$U(1)_X$, under which X and H' are charged, but not the SM fields, would yield such an enhancement. In the model discussed here, the $U(1)_X$ is unbroken, so we have a dark photon. As was recently discussed in [23], such dark forces can be consistent with observational constraints for dark coupling $\hat{\alpha} \lesssim 10^{-4}$. In the next section, we discuss in detail an alternative model where the mediator of the dark force is a broken symmetry, with the mediator having a mass in the GeV range. We now turn to a discussion of models where the dark forces arise from a broken symmetry in a hidden sector.

LITTLE GAUGE MEDIATION AND THE HDM SECTOR

In the previous section we introduced a simple model in which the two components of the dark matter come from the scalar and fermion components of a single chiral superfield X. Here we discuss extended dark matter models where the dark sector is more complicated, and symmetry breaking of the dark forces is possible. In addition to the heavy X sector, we turn to the effects of a hidden dark matter (hDM) sector.

With the addition of the hDM sector, the LSP of the extended MSSM plus X sector will no longer be stable by R-parity. We now take, however, both the fermionic and scalar component of X to be heavy, in the 500-800 GeV range. The scalar will be lighter than the fermionic component by loops of sleptons, S scalars, and H''s which give a negative mass-squared contribution to the $\tilde{X}$. The scalar X is thus the heavy component of DM, the lightest state odd under the Z_2.

For the purposes of this toy model, we consider the minimal hDM superpotential,

$$W_h = \lambda_D S_D \bar{D} D + \kappa_D S_D^3. \tag{4}$$

This hidden toy model is fashioned after that discussed in [16], and is to be added to the X-sector super-potential, Eq. (2). Here S_D is a dark singlet field, and $\bar{D}$, D may be charged under a new hidden gauge group $U(1)_D$, which is a dark force. $U(1)_D$ mixes with hypercharge through the kinetic term $\theta F_D^{\mu\nu} F_{\mu\nu}$. The lightest state in this sector will be stable, and a dark matter candidate.

This state may be an explanation for the DAMA signal, if its mass is in the 1-10 GeV range. This mass may naturally be induced radiatively from two sources. First, kinetic mixing between hypercharge and $U(1)_D$ is $\theta \sim 10^{-2} - 10^{-3}$, as expected when the mixing is induced by a loop of heavy particles [26]. This kinetic mixing introduces SUSY breaking into the hidden sector by a two loop diagram, as in [16]. We term this mechanism for SUSY breaking in the hidden sector "little gauge mediation." The size of the radiatively induced D, $\bar{D}$ masses is $m_{D,rad}^2 \sim g_D^2 g_Y^2 \theta^2 m_{SUSY}^2$, where $m_{SUSY} = \langle F_{mess}\rangle/(16\pi^2 M_{mess})$ is the SUSY breaking mass in the messenger sector, g_D is the gauge coupling of $U(1)_D$ and g_Y the hypercharge gauge coupling. With $\theta \sim 10^{-2} - 10^{-3}$, and $\mathcal{O}(1)$ couplings, we can see that the GeV mass scale is naturally generated in the hidden sector. In order to break $U(1)_D$, this mass-squared must be negative. One loop graphs with the scalar S_D in the loop may easily induce such a negative mass-squared, $m_{D,rad}^2 \sim -\frac{4\lambda_D^4 m_{S_D}^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_{SUSY}^2}\right)$, where Λ is the scale where the soft masses are generated, and $m_{S_D}^2$ is the soft SUSY breaking mass of S_D (we assume that the singlet receives a fairly large SUSY breaking mass through mixing with MSSM fields). For $\lambda_D \approx 10^{-1}$, soft masses for D in the few GeV range result which are negative, even with the contribution from little gauge mediation included.

With $\langle S_D\rangle = 0$ and $\langle D, \bar{D}\rangle \neq 0$, we review the spectrum briefly, but see [16] for details. With $\mathcal{O}(10^{-1-2})$ gauge coupling g_D and Yukawa term λ_D, all masses in the hidden sector are $\mathcal{O}(\mathrm{GeV})$. The $U(1)_D$ symmetry is broken by $\langle D, \bar{D}\rangle$ and the gauge boson acquires a mass. We have $m_{D,\bar{D}}^2 = -4\frac{g_D^2}{\lambda_D^2} m_{D,rad}^2$ and $m_{U_D}^2 = 4 g_D^2 \langle D\rangle^2$ from the breaking of the $U(1)_D$ with $\langle D, \bar{D}\rangle^2 = -m_{D,rad}^2/\lambda_D^2$. The fermion masses arise through $\tilde{D}, \tilde{\bar{D}}, \tilde{U}_D, \tilde{S}_D$ mixing, two with masses $2g_D\langle D\rangle$ and two with masses $\sqrt{2}\lambda_D\langle D\rangle$. We assume $g_D \lesssim \lambda_D$ so that the fermions with mass $2g_D\langle D\rangle$ are stable dark matter candidates. They are generate in mass with the D scalars and U_D gauge boson, which decay.

Now, we can see that such a sector can plausibly give rise to a signal in DAMA in the elastically scattering WIMP window. We take the $D - \tilde{S}_D$ fermions to be the dark matter with mass in the 3-10 GeV range. The DM may annihilate to the nearly degenerate in mass $\tilde{D}$ scalars, which then promptly decay. The annihilation cross-section is roughly $\sigma_{ann} \sim \frac{g_D^4}{4\pi}\frac{1}{m_{hDM}^2} \sim 10^{-35}\ \mathrm{cm}^2 \left(\frac{g_D}{0.1}\right)^4 \left(\frac{10\mathrm{GeV}}{m_{hDM}}\right)^2$, of the order $\sim 10^{-36}$ cm^2 necessary to produce the correct relic density (this candidate need not be all the dark matter). Indeed, this is as was observed in [17], for quite general reasons. The direct detection cross-section is

$$\begin{aligned}\sigma_{SI} &\simeq \frac{g_h^2 g_Y^2 \theta^2}{\pi}\frac{m_r^2}{m_U^4} \\ &\sim 10^{-39}\ \mathrm{cm}^2 \left(\frac{g_h g_Y \theta}{10^{-4}}\right)^2 \left(\frac{10\ \mathrm{GeV}}{m_U}\right)^4 \left(\frac{m_{hDM}}{5\ \mathrm{GeV}}\right)^2.\end{aligned} \tag{5}$$

We see that a hidden sector, which simultaneously generates natural GeV mediators and GeV scale dark matter candidates, produces a direct detection cross-section in a range to be the explanation for the DAMA signal.

The general conclusion here is that such hidden sectors with GeV mass dark matter particles and dark forces of GeV mass mediators arise naturally in a framework where the hidden sector communicates to the SM through kinetic mixing of dark force with hypercharge. The GeV scale is generated through radiative effects from the S_D scalars, and through this mixing, $m_{hDM} \sim \theta m_{SUSY}$. The mixing simultaneously provides motivation for observation of these states by direct detection experiments.

CONCLUSIONS

We have discussed multi-component dark matter models in which the dark sector is more complex than a single weakly interacting field. In many cases, these models give rise to additional dark forces which enrich the dark matter dynamics. Phenomenologically, the focus of this paper has been on explanations of the PAMELA, ATIC, PPB-BETS, HEAT, AMS, and DAMA excesses. In the models discussed here, the dark matter candidate which explains the positron excess carries lepton number; it may be stable either by an additional symmetry or by R-parity. We showed that in supersymmetric models of this type, there are naturally two dark matter candidates–the lighter candidate may explain the DAMA signal, and may be observable by low threshold runs of CDMS, XENON. We also showed how dark forces that arise in hidden sector dark matter models may naturally have their masses generated at the GeV scale, further motivating the low mass WIMP window as a well-motivated scale for direct detection of dark matter. Dark matter dynamics and dark matter sectors may be rich. As multiple experiments with varied detection techniques probe the dark sector, we may discover a dark hidden world in lieu of a single weakly interacting particle.

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